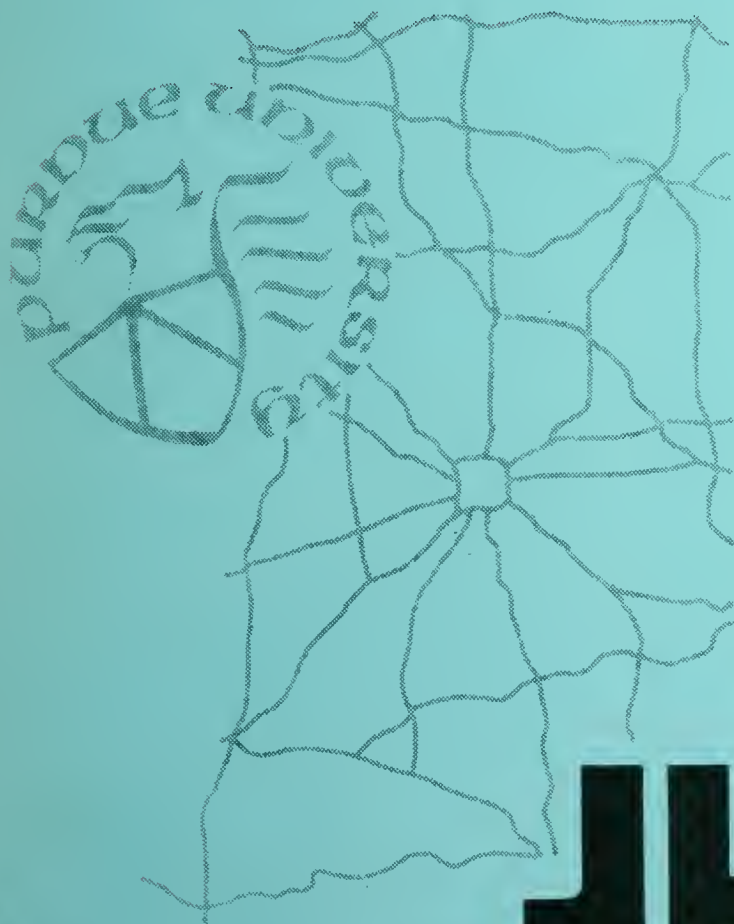


OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

SEPTEMBER 1969 — NUMBER 29



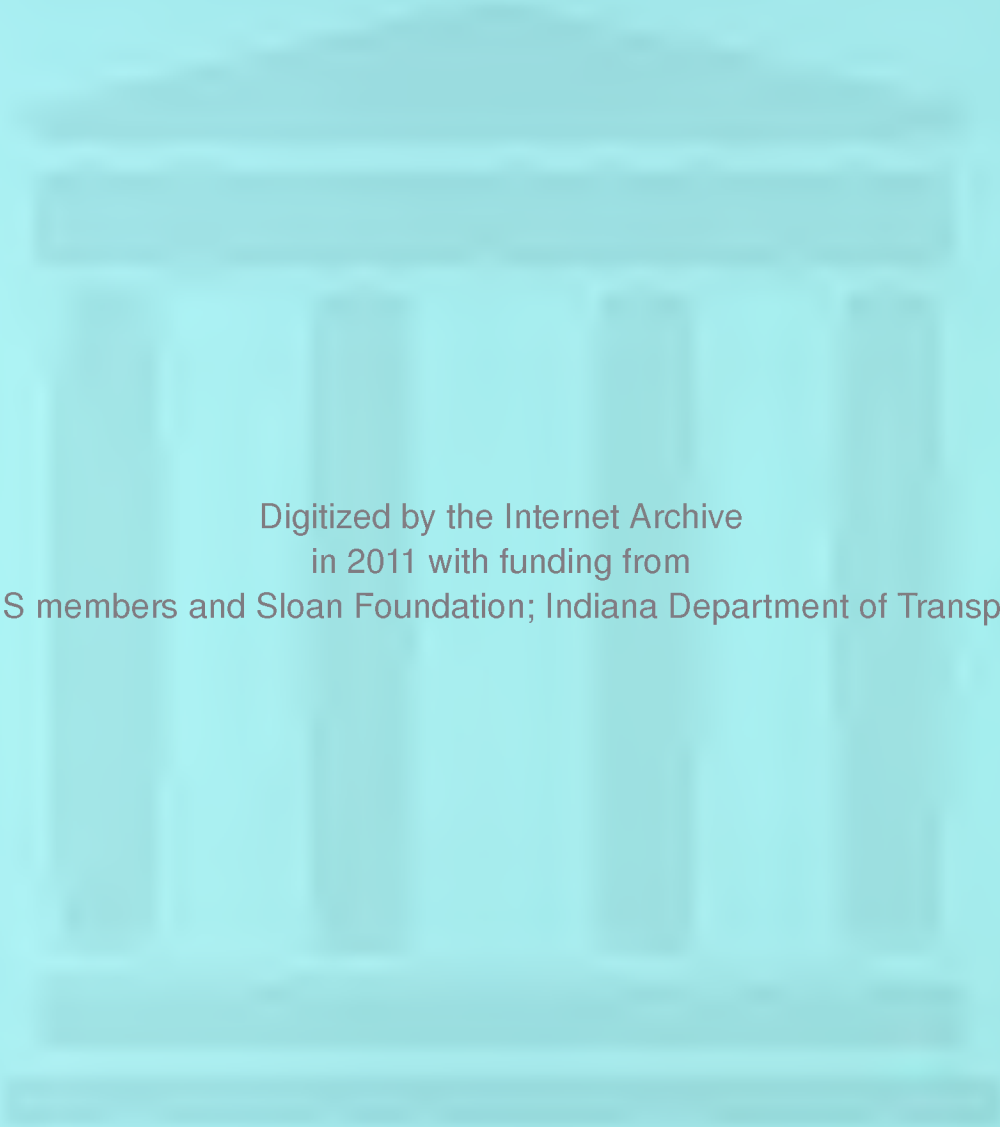
BY

S. S. HEJAL ,
S. R. YODER AND
J. C. OPPENLANDER

JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION



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OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

To: J. F. McLaughlin, Director
Joint Highway Research Project

September 18, 1969

Project No: C-36-52N

From: H. L. Michael, Associate Director
Joint Highway Research Project

File No: 6-20-9

The attached technical paper entitled "Optimal Design of Flexible Pavement Sections" has been prepared by Messrs. S. S. Hejazi, S. R. Yoder, and J. C. Oppenlander. The paper has been submitted to the Highway Research Board for presentation at the 1970 Annual Meeting and for subsequent publication. The purpose of this systems analysis was to develop a rational method for the optimal selection of flexible components. Minimum-cost thicknesses are determined for flexible pavements to satisfy the demands of traffic and environment on the system of pavement structure and soil support. Each flexible pavement section fulfills the design objectives for the least total cost.

The paper is presented to the Board for approval of presentation and publication by the Highway Research Board.

Respectfully submitted,



Harold L. Michael
Associate Director

RLM/rg

Attachment

Copy: F. L. Ashbaucher
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Technical Paper

OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

by

S. S. Hejal, S. R. Yoder, and J. C. Oppenlander

Joint Highway Research Project

Project No: C-36-52H

File No: 6-20-8

Purdue University

Lafayette, Indiana

September 18, 1969

OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

INFORMATIVE ABSTRACT

Although several methods are available for the design of flexible pavements, no existing technique explicitly considers the optimal combination of flexible pavement components to minimize the total in-place cost of the pavement system. The purpose of this systems analysis was to develop a rational method for the optimal selection of the arrangement of the various pavement components. This cost minimization must be realized within the boundary conditions that are imposed by the practical limitations of the design parameters.

The design model consists of an objective function and various constraint equations. The total cost of the pavement system is quantitatively described by this objective function, and a minimum-cost solution is obtained for each combination of material costs and design conditions. The various constraining equations quantify the boundary conditions to which the design of a flexible pavement is subject. These physical limitations complete the realism of the mathematical model in describing the real-world situation of flexible pavement design. The design model was solved by a modified linear programming technique.

In developing practical solutions to the design model, optimal flexible pavements are designed for cross-sections without subbase, cross-sections with subbase through shoulders, and cross-sections with subbase and subdrains. The design requirements for the various components are predicated on the design parameters of traffic conditions, soil support values, pavement material characteristics, environmental effects, and

pavement performance requirements and on unit costs of pavement components. Substantial cost savings result in the selection of flexible pavement sections by this design procedure.

OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

INTRODUCTION

The primary objective of highway pavement design is to provide an acceptable roadway surface that can withstand the deteriorating effects of traffic and environment for the service life of the facility. In addition, the pavement structure must adequately serve the demands of the road users at an acceptable level of performance. A properly designed, constructed, and maintained pavement is a major factor in providing economical, efficient, safe, convenient, and comfortable highway travel. This goal is an integral part of the total highway transportation program.

Although several design techniques are available for determining reasonable thicknesses of flexible pavements to satisfy the specified design parameters, no present method explicitly considers an optimization of flexible pavement components to minimize the total cost of the pavement system. Of course, this cost minimization must be realized within the boundary constraints imposed by the selected values of the design parameters. The purpose of this systems analysis was to develop a rational method for the optimal design of flexible pavement sections.

The objective of flexible pavement design in this investigation is to select the various pavement components so that the total pavement cost is minimized within the limitations of the various design parameters. Minimum-cost designs are determined for flexible pavements to satisfy the demands of traffic and environment on the system of pavement structure and soil support. Therefore, this technique affords a

practical and economical solution to the problem of designing flexible pavements. This approach to design embodies the essence of sound engineering.

CONCEPTUAL MODEL

A flexible pavement distributes the traffic loads through a system of pavement components to the subgrade. These pavement layers are generally identified as surface, base, and subbase. Several different thickness combinations of the materials comprising the various components may adequately satisfy the structural design of the highway pavement. However, all satisfactory thickness arrangements may not provide an economical solution to the engineering problem of pavement design. In general, only one pavement structure is an optimal selection of the flexible pavement components for the designated design conditions.

The concept for this Flexible pavement design procedure is illustrated by the logic diagram in Figure 1. The total pavement system is described by the various design parameters which represent traffic conditions, soil support values, pavement material characteristics, environmental effects, and pavement performance requirements. In addition, unit costs of pavement components and alternate cross-section designs are considered in the selection of the optimum flexible pavement section.

The structural requirements of flexible pavements are predicated on an estimated number of equivalent 18-kip single-axle load repetitions and on an appropriate measure of the soil support afforded by the subgrade. The elements of pavement performance and environment are also incorporated as initial and terminal serviceabilities and regional factor, respectively. The combined effect of traffic loading, soil support, pavement performance, and environment is denoted as a structural number (SN) according to the interim design guide of the American

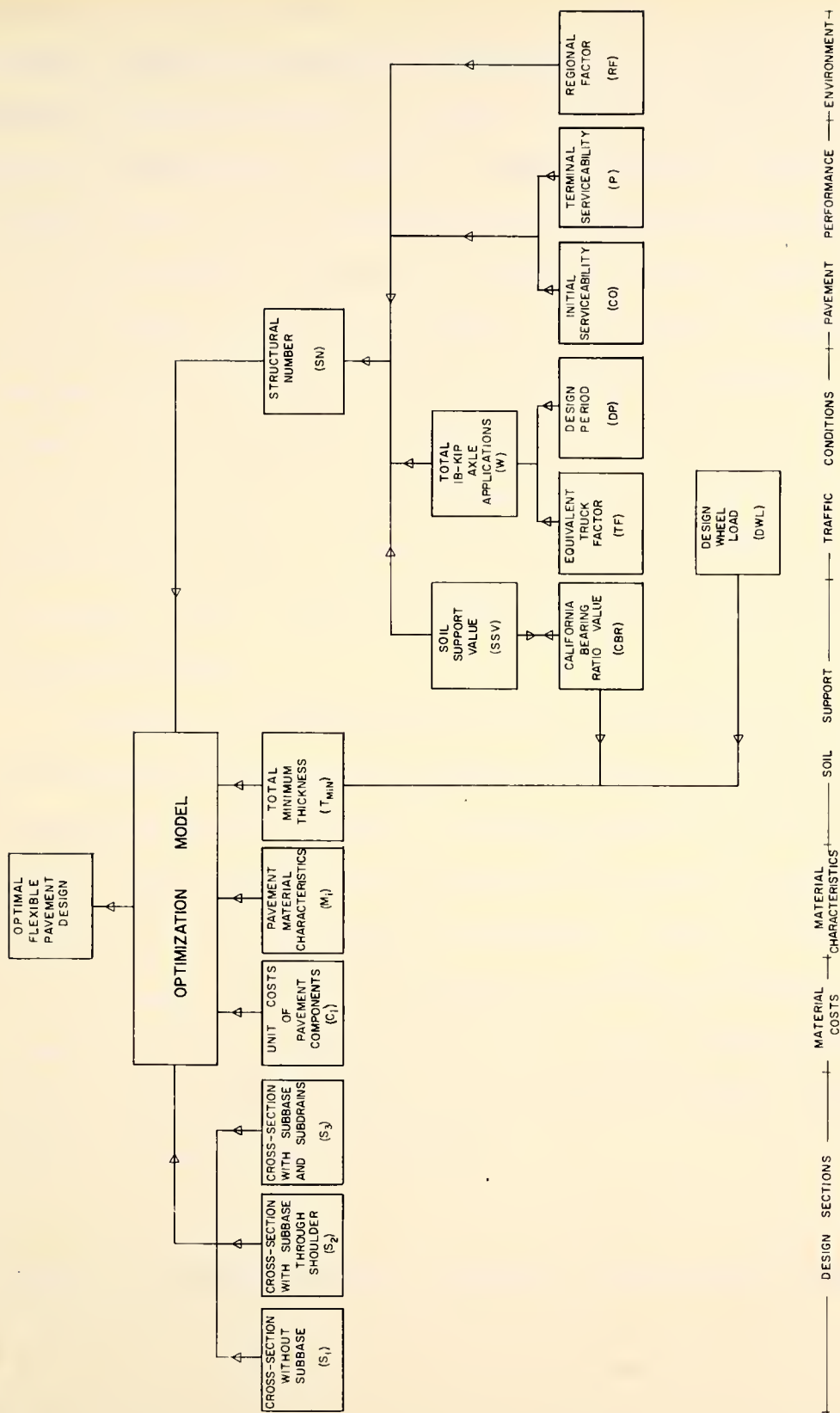


Figure 1

Association of State Highway Officials for flexible pavements. (1)*

Pavement component thicknesses are then selected to reproduce the specified structural number by a linear combination of layer thickness times its coefficient of relative strength. A minimum pavement thickness is equal to the summation of the component thicknesses.

Consideration of significant environmental factors, such as depth of frost penetration, provides another control on the selection of a minimum pavement thickness. This design procedure specifies a minimum pavement thickness (T_{min}) to account for various influencing environmental conditions. This minimum thickness is based on a design procedure which requires a selected design wheel load and a specified soil support value. The greater minimum thickness value becomes the design requirement.

To account for varying design practices, several types of pavement cross-sections are available as possible alternatives in this procedure for designing flexible pavements. These arrangements include cross-sections without subbase, cross-sections with subbase through shoulders, and cross-sections with subbase and subdrains. Finally, the unit costs of the pavement components are specified to permit the design of an acceptable pavement structure for the least cost. This cost-effectiveness approach provides both an optimal and a practical solution to the problem of flexible pavement design.

*Numbers in parentheses refer to articles listed in the Bibliography.

In a real sense, the minimum thicknesses represent design constraints and not design objectives. The design objective is to produce a flexible pavement system at the least total cost within the specified boundary conditions. The in-place unit costs of the component materials depend on the locale in which the flexible pavement is to be constructed. In addition to the traffic loading, soil support, pavement performance, and environment constraints, practical limitations on layer thicknesses are specified in concurrence with present highway construction practices.

DESIGN MODEL

The logic diagram for this optimal design of flexible pavements is structured in Figure 1. A detailed description of this design technique is presented under the following categories of Design Parameters, Design Sections, and Optimization Model. These sections provide the various computational procedures and design features for determining the optimal selection of flexible pavement sections.

Design Parameters

The design parameters represent the various measures of traffic conditions, soil support, pavement material properties, environmental effects, and pavement performance requirements. The results of these evaluations provide the summary quantities that are necessary for the optimal design of flexible pavements.

The initial measure of the stability of the subgrade soil is determined by the standard California bearing ratio test. This soil strength is then translated into the soil support value (SSV) as defined by the American Association of State Highway Officials. (1) In this study the following equation was developed to relate soil support values to California bearing ratio measures:

$$SSV = 4.90 \log_{10} (CBR)$$

where SSV = soil support value and

CBR = California bearing ratio.

The traffic conditions are expressed as the number of 18-kip single-axle load repetitions for the service life of the pavement. These load applications are estimated from an evaluation of the following formula:

$$W = 365 (TF) (DP)$$

where W = total number of equivalent 18-kip single-axle load repetitions during the pavement design period,

TF = truck factor (18-kip single-axle load applications per day), and

DP = design period (years).

To develop a measure of the truck factor, a correlation was derived between the number of 18-kip single-axle load applications and the percentages of various truck types in the traffic streams. The following expression was obtained from loadometer data collected on highways in Indiana:

$$TF = \left[\frac{(ADT_1) + (ADT_2)}{4} \right] \left[\frac{11.7(TR)(LU) + 0.83(TR)(LU)(CT)}{10,000} \right]$$

where TF = truck factor (18-kip single-axle load applications per day),

ADT₁ = average daily traffic volume at the start of the design period (vehicles per day in both directions),

ADT₂ = average daily traffic volume at the end of the design period (vehicles per day in both directions),

TR = percentage of all trucks,

CT = percentage of combination trucks, and

LU = truck lane usage factor (1.0, 0.9, and 0.8 for two-, four-, and six-lane highways, respectively).

The various measures of traffic conditions, soil support, environmental effects, and pavement performance requirements are now combined into a single design parameter defined as the structural number (SN). Two nomographs have been prepared by the American Association of State Highway Officials to quantify this structural requirement. (1) However, the following equation was developed from these nomographs to use in the computer program for this design procedure:

$$\log_{10}(W) = 9.36 \log_{10} [(SN) + 1] - 0.20$$

$$+ \log_{10} \left[\frac{(CO) - (P)}{(CO) - 1.5} \right] \left/ \left[0.60 + \frac{109}{[(SN) + 1]^{5.19}} \right] \right.$$

$$\left. + 0.37756 [(SSV) - 3.0] - 0.97 \log_{10} (RF) \right]$$

where W = total number of equivalent 18-kip single-axle

load repetitions during the pavement design period,

SN = structural number,

CO = initial pavement serviceability index (4.2 for all highways),

P = terminal pavement serviceability index,

SSV = soil support value, and

RF = regional factor. (2)

The effects of the environment are numerically summarized in the regional factor, and the desired pavement performance is specified by selected values for the initial and terminal pavement serviceability indices. An iterative procedure is used to solve the above equation for the structural number of a particular design situation.

Another consideration of environmental influences is to determine a minimum thickness as a design against the detrimental effects of frost action and the loss of subgrade strength in the spring break-up period. Design charts that were developed by L. D. Hicks provide correlations between bearing capacity and California bearing ratio and between pavement thickness and bearing capacity. (3) Adverse subgrade conditions are represented by using a two-day soaked value for the selected California bearing ratio. The following relationships were prepared from these design charts for 9-kip and 10-kip wheel loads, respectively:

$$T_{\min.}(9) = 4.723 + \frac{61.037}{(\text{CBR})^{1.05}} - 45.18 e^{-(\text{CBR})}$$

$$T_{\min.}(10) = 4.423 + \frac{52.706}{(\text{CBR})^{0.90}} - 19.884 e^{-(\text{CBR})}$$

where $T_{\min.}(9)$ = minimum pavement thickness for 9-kip design wheel load (inches),

$T_{\min.}(10)$ = minimum pavement thickness for 10-kip design wheel load (inches), and

CBR = California bearing ratio for reduced strength conditions.

The 10-kip wheel load is considered satisfactory for the design of primary highways, while the 9-kip wheel load is applicable for flexible pavements on secondary routes. In the computer input for this design

model, the highway engineer specifies the design wheel load for either a primary or a secondary highway. This minimum-thickness determination accounts for environmental effects by highway classification and provides another realistic constraint in selecting optimal flexible pavement sections.

The characteristics of each pavement material are described by the in-place density and the coefficient of relative strength. These values depend on the local materials that are used in the construction of flexible pavements. The evaluation of the pavement material characteristics permits the application of the design model for the prevailing construction practices.

The above descriptions numerically define the various design components of the flexible pavement system. Although the selected equations provide reasonable evaluations of these parameters, other expressions can be used to satisfy local design conditions.

Design Sections

Because reasonable variations exist in the design of highway elements, three acceptable cross-sections were selected for two-lane and divided multi-lane highways to provide several alternative designs in the model. These arrangements include the following distinct designs:

1. Cross-sections without subbase (S_1),
2. Cross-sections with subbase (S_2)
 - a. Extended through the shoulders for two-lane highways and
 - b. Extended through the right shoulder with subdrain under the left shoulder for divided multi-lane highways, and

3. Cross-sections with subbase and subdrains under both shoulders. Typical details of these cross-sectional designs are illustrated in Figures 2, 3, 4, and 5, respectively. The shoulder designs are further detailed in Figure 6 for cross-sections with subbases and with subdrains.

Of course, additional cross-sectional arrangements may be incorporated into this design model. Because each section represents a different design, an objective function is required for each cross-section to permit the optimal selection of flexible pavement sections. The best design is then that cross-section which minimizes the total pavement cost for the specified design parameters.

Optimization Model

The optimal design of flexible pavement sections is depicted by the following objective functions for the three different design sections:

1. Cross-sections without subbase;

$$\begin{aligned} \text{Min. } S_1 = & \left[\frac{C_1 D_1 L k_1}{12 \times 2000} \right] d_1 + \left[\frac{C_2 D_2 L k_2}{12 \times 2000} \right] d_2 \\ & + \left[\frac{C_3 D_3 L k_3}{12 \times 2000} \right] d_3 + E_f + H_f \end{aligned}$$

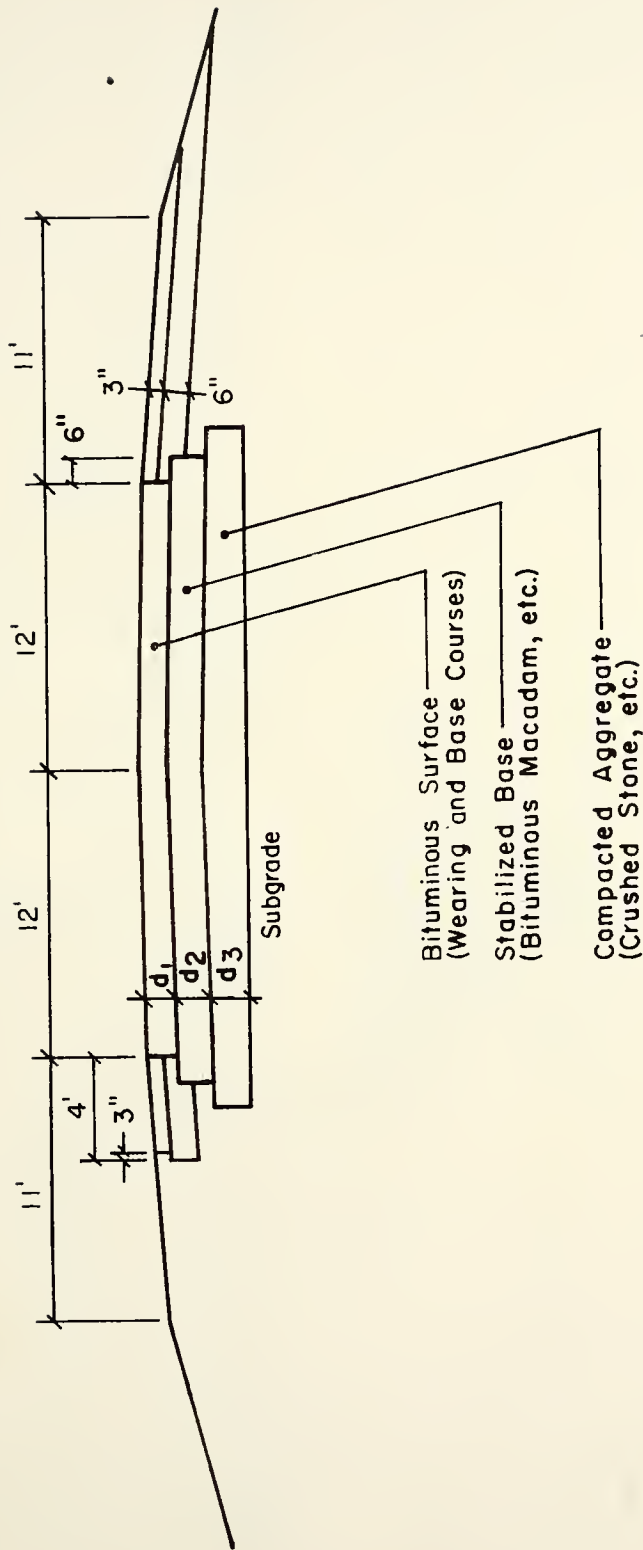


Figure 2 Typical Cross-Section Of A Flexible Pavement Without Subbase
For A Four-Lane Highway, One Direction.

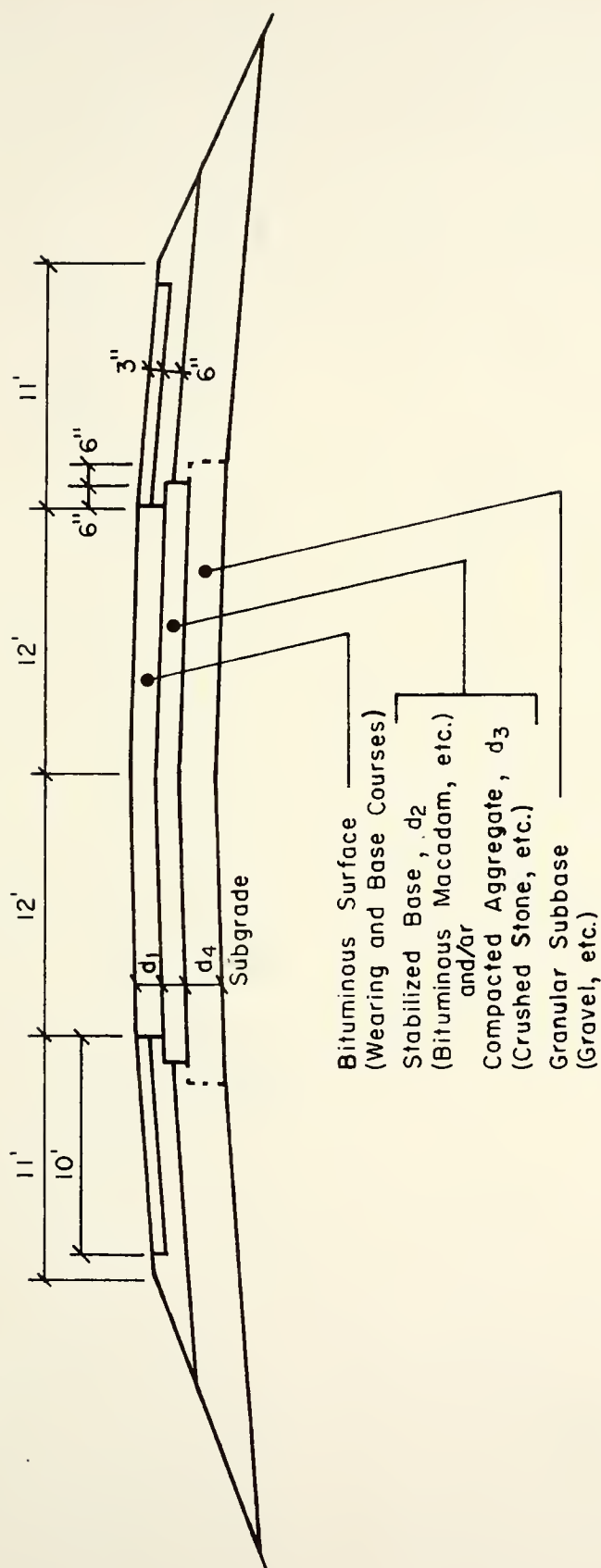


Figure 3 Typical Cross-Section Of A Flexible Pavement With Subbase Through The Shoulder For A Two-Lane Highway.

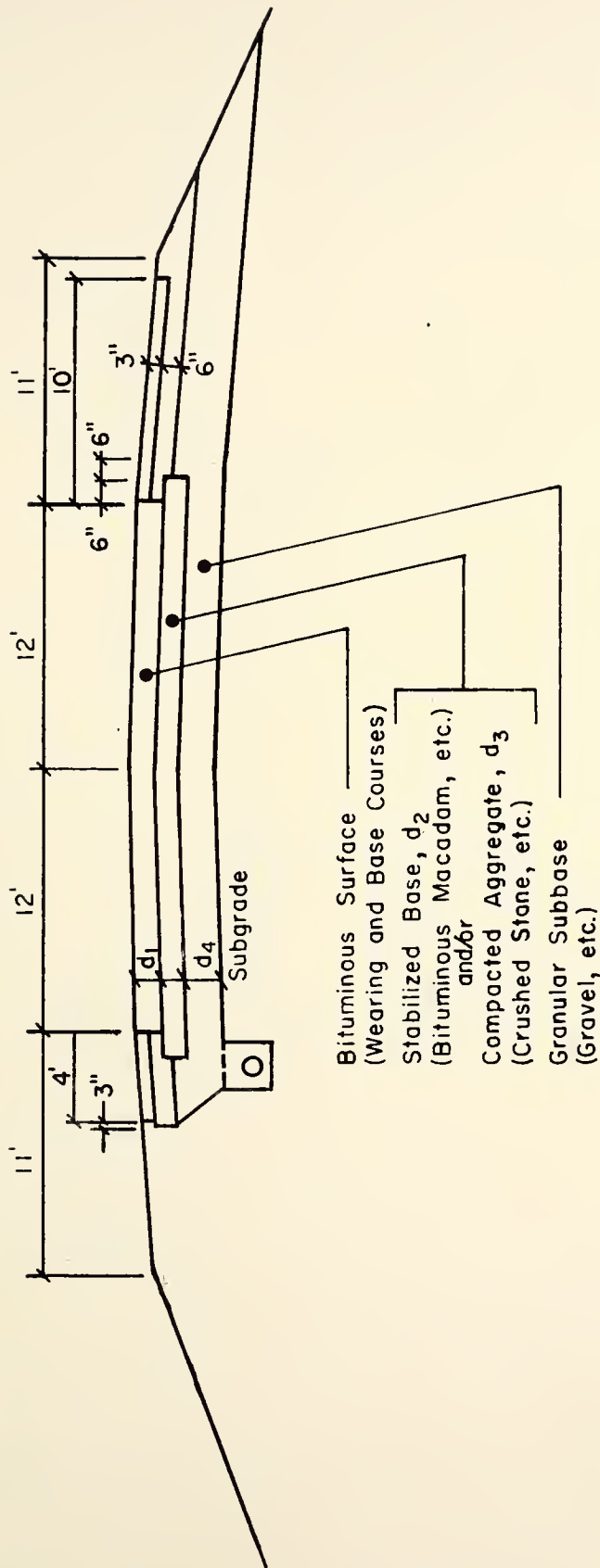


Figure 4 Typical Cross-Section Of A Flexible Pavement With Subbase Through The Shoulder For A Four-Lane Highway, One Direction.

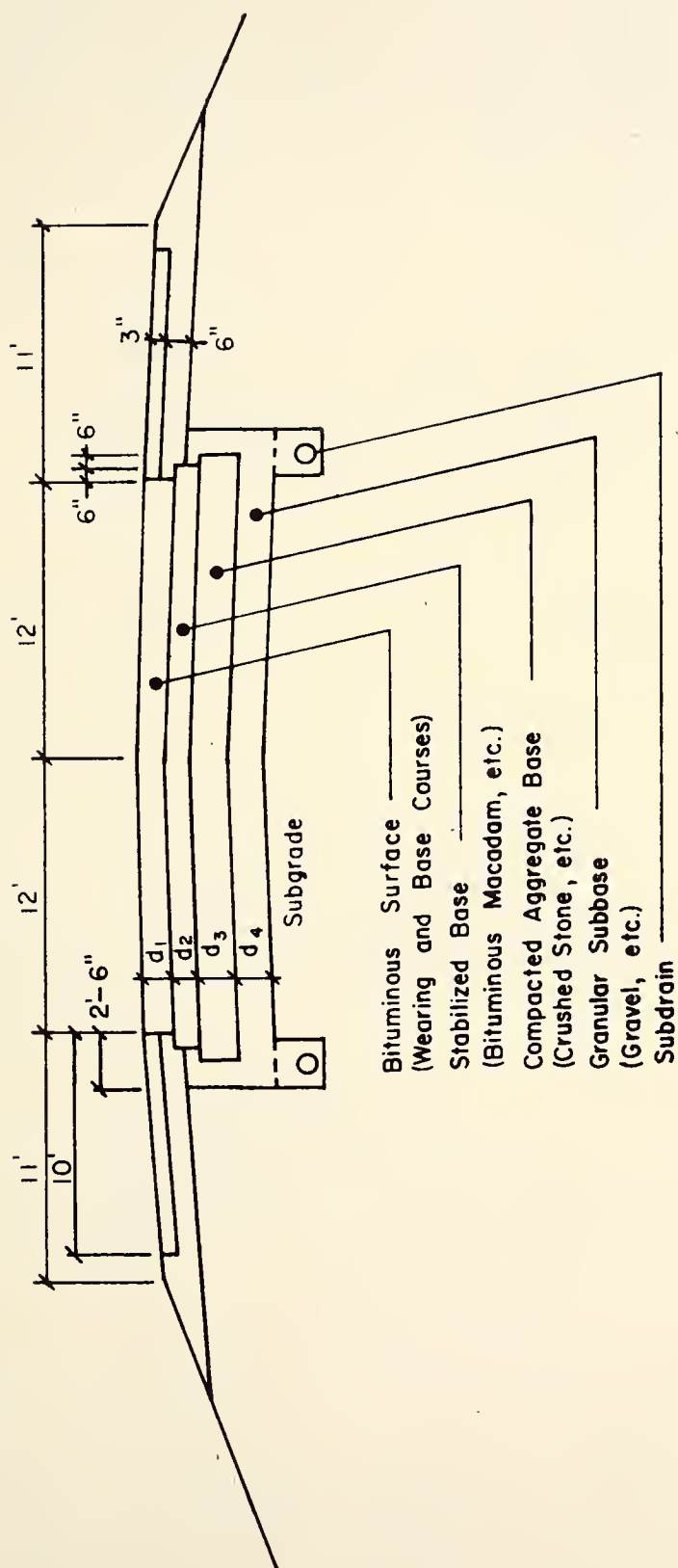


Figure 5 . Typical Cross Section Of A Flexible Pavement With Subbase Drain For A Two-Lane Highway.

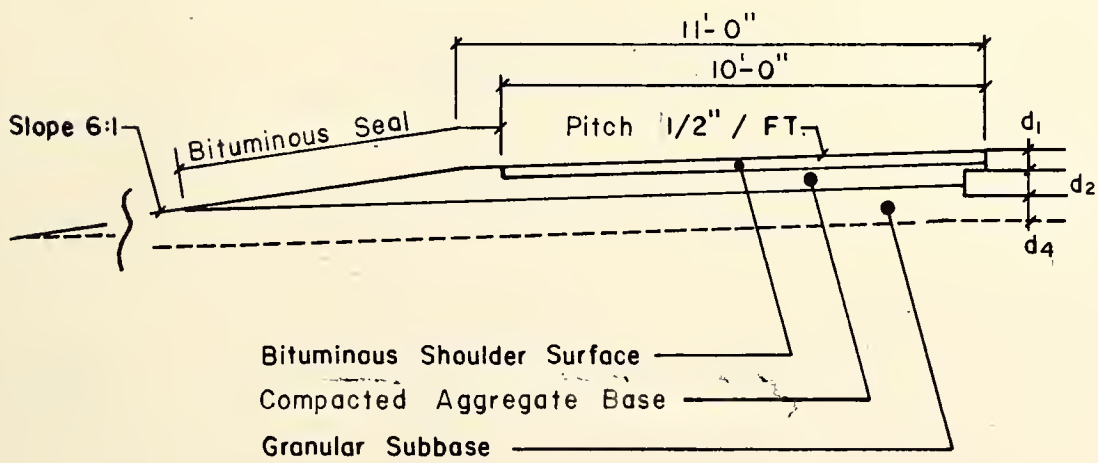
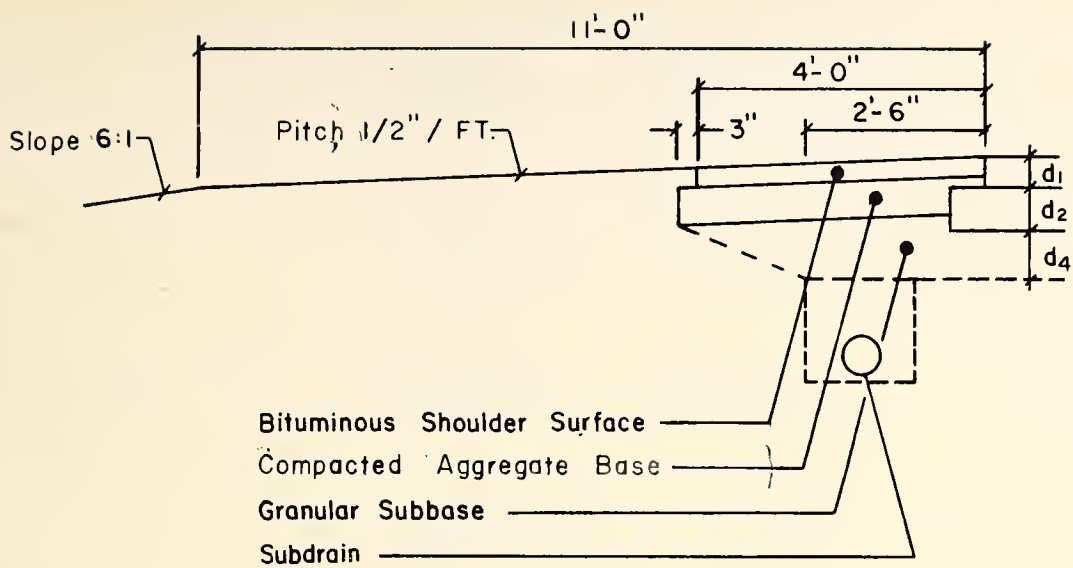


Figure 6 Shoulder Details.

2. Cross-sections with subbase through shoulders;

$$\begin{aligned}
 \text{Min. } S_2 = & \left[\frac{C_1 D_1 L k_1}{12 \times 2000} + \frac{C_4 A}{12 \times 27} \right] d_1 \\
 & + \left[\frac{C_2 D_2 L k_j}{12 \times 2000} + \frac{C_4 A}{12 \times 27} \right] d_2 \\
 & + \left[\frac{C_3 D_3 L k_j}{12 \times 2000} + \frac{C_4 A}{12 \times 27} \right] d_3 \\
 & + \left[\frac{C_4 (L+A)}{12 \times 27} \right] d_4 + E_\ell + H_\ell + M_\ell - Y_\ell
 \end{aligned}$$

3. Cross-sections with subbase and subdrains;

$$\begin{aligned}
 \text{Min. } S_3 = & \left[\frac{C_1 D_1 L k_1}{12 \times 2000} + \frac{C_4 B}{12 \times 27} \right] d_1 \\
 & + \left[\frac{C_2 D_2 L k_j}{12 \times 2000} + \frac{C_4 B}{12 \times 27} \right] d_2 \\
 & + \left[\frac{C_3 D_3 L k_j}{12 \times 2000} + \frac{C_4 B}{12 \times 27} \right] d_3 \\
 & + \left[\frac{C_4 (L+B)}{12 \times 27} \right] d_4 + E_\ell + H_\ell + N - Z_\ell
 \end{aligned}$$

where S = total cost of pavement system (dollars per longitudinal foot),

C_i = unit cost of material 'i' (dollars per ton for materials 1, 2, 3, 5, and 8, dollars per cubic yard for materials 4 and 6, and dollars per foot for material 7),

I_1 = density of material 1 (pounds per cubic foot);

I = pavement width (ft) for two-lane and one-way sections of divided multi-lane highways and 36 ft for one-way section of divided multi-lane highways;

d_1 = thickness of material 1 (inches);

j = 1 for bituminous surface, 2 for stabilized base, 3 for compacted aggregate base, 4 for granular subbase, 5 for bituminous shoulder surface, 6 for subdrain granular fill, 7 for subdrain pipe, and 8 for wearing surface;

k_j = adjustment factor for decrease in width of pavement layers;

k_1 = 1.00 for first layer;

k_2 = 1.04 for second layer;

k_3 = 1.08 for third layer, and

k_4 = 1.12 for fourth layer;

E_s = cost of shoulder (dollars per longitudinal foot);

For two-lane highways;

$$E_1 = 20 \times 3.0 \left[\frac{C_1 D_1}{12 \times 2000} \right] \\ + 31 \times 6.0 \left[\frac{C_3 D_3}{12 \times 2000} \right]$$

For divided multi-lane highways;

$$E_2 = 14 \times 3.0 \left[\frac{C_2 D_2}{12 \times 2000} \right] \\ + 19.75 \times 6.0 \left[\frac{C_3 D_3}{12 \times 2000} \right]$$

H_e = adjustment for the additional cost of the wearing surface,

For two- and four-lane highways;

$$H_1 = \frac{(C_8 - C_1)}{12 \times 2000} \cdot P_1 \times \left(\frac{90}{110}\right) \times 2$$

For six-lane highways;

$$H_2 = \frac{(C_8 - C_1)}{12 \times 2000} \cdot P_1 \times \left(\frac{90}{110}\right) \times 36$$

A_s = width of shoulder subbase for an embankment slope of 6:1 (feet),

For two-lane highways;

$$A_1 = \left[22 + \frac{2(d_1 + d_2 + d_3)}{3} \right]$$

For divided multi-lane highways;

$$A_2 = \left[14.375 + \frac{(d_1 + d_2 + d_3)}{3} \right]$$

B_s = adjusted width of shoulder subbase when subdrains are provided (feet),

For two-lane highways;

$$B_1 = 5.0$$

For divided multi-lane highways;

$$B_2 = 5.875$$

M_s = cost of subdrain when used under median shoulder only (dollars per longitudinal foot),

For two-lane highways;

$$M_1 = 0.0$$

For divided multi-lane highways;

$$M_2 = 1.1 (0.075 C_6 + C_7)$$

N = cost of subdrains under both shoulders (dollars per longitudinal foot),

For all highways;

$$N = 2 \times 1.1 (0.075 C_6 + C_7)$$

Y_ℓ = adjustment for the amount of subbase material replaced by the shoulder surface and base (dollars per longitudinal foot), and

For two-lane highways;

$$Y_1 = \frac{253 \times C_4}{12 \times 27}$$

For divided multi-lane highways;

$$Y_2 = \frac{162 \times C_4}{12 \times 27}$$

Z_ℓ = adjustment for the amount of subbase material added above the level of the pavement subbase under the shoulders.

For two-lane highways;

$$Z_1 = \frac{50 \times C_4}{12 \times 27}$$

For divided multi-lane highways;

$$Z_2 = \frac{60 \times C_4}{12 \times 27}$$

Thus, the objective of this optimal selection of flexible pavement components is to minimize the total cost of the pavement system. The various material and layer notations of the design model are graphically described in the figures which illustrate the design sections.

To quantify the boundary conditions to which the optimal design of the flexible pavement components is subject, the following constraint equations are necessary to complete the realism of this design model.

1. The selection of layer thicknesses must satisfy the structural number requirement.

$$a_1 d_1 + a_2 d_2 + a_3 d_3 + a_4 d_4 \geq SN$$

where a_i = coefficient of relative strength of material 'i'

and

SN = structural number for design.

The coefficients of relative strength are presented in Table 1 for the four pavement materials used in this design model.

2. The total thickness of the flexible pavement must be at least equal to the minimum thickness which is required by an influencing environmental consideration.

$$d_1 + d_2 + d_3 + d_4 \geq T_{\min}$$

where $T_{\min}$ = total minimum thickness of flexible pavement to satisfy environmental conditions.

The remaining constraining equations are required to account for the physical limitations inherent in the construction of the various layers of a flexible pavement. The following seven relationships complete the mathematical representation of the concept for the optimal selection of flexible pavement components.

Table 1

PAVEMENT MATERIAL SPECIFICATIONS

Material Notation	Material Description	Coefficient of Relative Strength (a_1)
d_1	Bituminous surface	0.44
d_2	Stabilized base	0.24
d_3	Compacted aggregate base	0.14
d_4	Granular subbase	0.08

3. The bituminous surface course of a primary highway is at least 3.0 in. in thickness.

$$d_1 \geq 3.0$$

4. If a stabilized base is selected for the pavement system, the minimum thickness is 4.0 in.

$$d_2 = 0 \text{ or } \geq 4.0$$

5. If a compacted aggregate base is included in the flexible pavement, a minimum thickness of 4.0 is necessary for construction purposes.

$$d_3 = 0 \text{ or } \geq 4.0$$

6. If a granular subbase is specified from the optimal selection, at least a 4.0-in. layer is required.

$$d_4 = 0 \text{ or } \geq 4.0$$

7. Because rutting and shoving of the pavement surface may result under high load repetitions for excessive thicknesses of bituminous mixtures, the maximum thickness of the bituminous surface is 10.0 in.

$$d_1 \leq 10.0$$

8. The maximum thickness of the stabilized base is established at 10.0 in. because of large vertical deformations that may result in this base course if excessive thicknesses of bituminous mixtures are used.

$$d_2 \leq 10.0$$

9. An upper limit of 20.0 in. is set for the thickness of the granular subbase to conform with present construction practice in the State of Indiana.

$$d_4 \leq 20.0$$

In summary, the optimal design of flexible pavement components is predicated on determining that minimum-cost combination of layer thicknesses which satisfy the real and practical constraining conditions. The selection of actual in-place construction costs enhances the mathematical representation of the flexible pavement design process and provides further economies in the highway construction industry.

SOLUTION

The final step in determining the optimal design of flexible pavement sections is to obtain a solution to the design model. This solution optimizes the objective function and is subject to the set of constraining situations. The design model was programmed for solution on digital computers using FORTRAN IV language.

The optimization process is performed in two stages. In the first phase, the following nine separate arrangements of flexible pavement components are optimized by a linear programming algorithm.

1. Bituminous surface and stabilized base;
2. Bituminous surface, stabilized base, and compacted aggregate base;
3. Bituminous surface, stabilized base, and granular subbase with subbase through shoulders;
4. Bituminous surface, stabilized base, and granular subbase with subdrains;
5. Bituminous surface, stabilized base, compacted aggregate base, and granular subbase with subbase through shoulders;
6. Bituminous surface, stabilized base, compacted aggregate base, and granular subbase with subdrains;
7. Bituminous surface and compacted aggregate base;
8. Bituminous surface, compacted aggregate base, and granular subbase with subbase through shoulders; and
9. Bituminous surface, compacted aggregate base, and granular subbase with subdrains.

Six of these nine layered combinations of pavement components represent all possible flexible pavement systems for the cross-sections with subbase (S_2) and for the cross-sections with subbase and subdrains under both shoulders (S_3). Only three arrangements of these components are possible for the cross-sections without subbase (S_1) and include combinations 1, 2, and 7.

The other phase of the solution involves the selection of that pavement-component arrangement which minimizes the total cost of the pavement system for the selected unit costs of the pavement materials. This final solution represents the global optimum, and no better solution exists for the specified pavement design and material cost parameters. Each flexible pavement section fulfills the design objectives for the least total cost.

DESIGN EXAMPLES

To illustrate the application of this design model, two typical examples are presented for the design of flexible pavements. In each case, the computer output provides a listing of the stipulated design data and the material specifications. After these design parameters are summarized, the optimal solution is tabulated in terms of the best design section and the required thicknesses of the pavement components. To permit a cost-effectiveness evaluation, the next two best solutions are generated for the remaining design sections. These alternate suboptimal solutions provide an economic measure of the additional cost for designs other than the optimal cross-section.

The first situation involves a two-lane highway with a primary classification. The other example is a four-lane highway with pavement material costs that differ from those corresponding values in the first illustration. The rather significant increases in flexible pavement costs are evident when the alternate suboptimal solutions are compared to the optimal solutions in the preceding two design examples.

Real economies are achieved when engineering designs are formulated to permit the selection of the optimal answer. This design model affords the highway engineer with a practical and realistic method for the optimal design of flexible pavement sections.

DESIGN OF FLEXIBLE PAVEMENT
FOR PRIMARY HIGHWAYS

DESIGN DATA

NUMBER OF LANES	2	
CBR	4.00	
AVERAGE DAILY TRAFFIC 1966	2900.	VEH./DAY BOTH DIRECTIONS
AVERAGE DAILY TRAFFIC 1986	5220.	VEH./DAY BOTH DIRECTIONS
DESIGN PERIOD	20.00	YEARS
PERCENT TRUCKS	20.00	
PERCENT MULTIPLE UNITS	25.00	
DESIGN WHEEL LOAD	10000.	LB.
REGIONAL FACTOR	1.00	
PAVEMENT TERMINAL SERVICABILITY	2.50	

MATERIALS SPECIFICATIONS

	COST	DENSITY
BITUMIN. WEARING SURFACE	10.00 \$/TON	145. LB/FT ³
BITUMINOUS SURFACE BASE	9.00 \$/TON	145. LB/FT ³
STABILIZED BASE	8.00 \$/TON	135. LB/FT ³
COMPACTED AGGREGATE BASE	3.25 \$/TON	140. LB/FT ³
GRANULAR SUBBASE	3.15 \$/YD ³	
SHOULDER SURFACE	8.50 \$/TON	145. LB/FT ³
AGGREGATE FOR SUBDRAIN .	5.00 \$/YD ³	
PIPES FOR SUBDRAIN	0.70 \$/FT	

Example 1

SOLUTION

NUMBER OF LANES	2
PERCENT MULTIPLE UNITS	25.00
STRUCTURAL NUMBER	3.95
TOTAL THICKNESS	19.2 INCHES
TRUCK FACTOR	132. LBK/DAY

OPTIMAL SOLUTION

CROSS-SECTION WITHOUT SUBBASE

	THICKNESS
BITUMINOUS SURFACE	4.2 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	15.0 INCHES
GRANULAR SUBBASE	0. INCHES

COST .. 19.32 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBRAIN

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 21.45 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBBASE THRU GH SHOULDER

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 22.63 \$ PER LONG. FT.

Example 1 (Cont.)

SOLUTION

NUMBER OF LANES	2
PERCENT MULTIPLE UNITS	25.00
STRUCTURAL NUMBER	3.95
TOTAL THICKNESS	19.2 INCHES
TRUCK FACTOR	132. 1BK/DAY

OPTIMAL SOLUTION

CROSS-SECTION WITHOUT SUBBASE

	THICKNESS
BITUMINOUS SURFACE	4.2 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	15.0 INCHES
GRANULAR SUBBASE	0. INCHES

COST .. 19.32 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBDRAIN

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 21.45 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBBASE THROU GH SHOULDER

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 22.63 \$ PER LONG. FT.

Example 1 (Cont.)

DESIGN OF FLEXIBLE PAVEMENT
FOR PRIMARY HIGHWAYS

DESIGN DATA

NUMBER OF LANES	4	
CBR	2.30	
AVERAGE DAILY TRAFFIC 1968	9438.	VEH./DAY BOTH DIRECTIONS
AVERAGE DAILY TRAFFIC 1988	17830.	VEH./DAY BOTH DIRECTIONS
DESIGN PERIOD	20.00	YEARS
PERCENT TRUCKS	17.00	
PERCENT MULTIPLE UNITS	50.00	
DESIGN WHEEL LOAD	10000.	LB.
REGIONAL FACTOR	1.00	
PAVEMENT TERMINAL SERVICABILITY	2.50	

MATERIALS SPECIFICATIONS

	COST	DENSITY
BITUMIN. WEARING SURFACE	6.85 \$/TON	145. LB/FT ³
BITUMINOUS SURFACE BASE	5.92 \$/TON	145. LB/FT ³
STABILIZED BASE	5.53 \$/TON	135. LB/FT ³
COMPACTED AGGREGATE BASE	2.87 \$/TON	140. LB/FT ³
GRANULAR SUBBASE	3.33 \$/YD ³	
SHOULDER SURFACE	7.95 \$/TON	145. LB/FT ³
AGGREGATE FOR SUBDRAIN .	4.35 \$/YD ³	
PIPES FOR SUBDRAIN	0.72 \$/FT	

Example 2

SOLUTION

NUMBER OF LANES	4
PERCENT MULTIPLE UNITS	50.00
STRUCTURAL NUMBER	5.67
TOTAL THICKNESS	27.3 INCHES
TRUCK FACTOR	555. 1BK/DAY

OPTIMAL SOLUTION

CROSS-SECTION WITHOUT SUBBASE

	THICKNESS
BITUMINOUS SURFACE	6.1 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	21.2 INCHES
GRANULAR SUBBASE	0. INCHES

COST .. 18.25 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBDRAIN

	THICKNESS
BITUMINOUS SURFACE	9.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	14.3 INCHES

COST .. 20.39 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBBASE THROUGH SHOULDER

	THICKNESS
BITUMINOUS SURFACE	9.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	14.3 INCHES

COST .. 23.14 \$ PER LONG. FT.

Example 2 (Cont.)

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2. Buick, T. R., "Analysis and Synthesis of Highway Pavement Design," a Thesis submitted to Purdue University for the degree of Master of Science in Civil Engineering, June 1968.
3. Hicks, L. D., "Structural Design of Flexible Pavements in North Carolina," Proceedings, International Conference on the Structural Design of Asphalt Pavements, University of Michigan, August 1962.

APPENDIX A
COMPUTER PROGRAM

MAIN - EFN SOURCE STATEMENT - IFN(S) -

120X.26HCOMPACTED AGGREGATE BASE ,F5.2,6H \$/TCN,F10.0,7H LR/FT3,/
120X.26FGRANULAR SUBBASE ,F5.2,6H \$/YD3,/
120X.26FSHOULDER SURFACE ,F5.2,6H \$/TCN,F10.0,7H LR/FT3,/
120X.26HAGGREGATE FOR SUBDRAIN ,F5.2,6H \$/YC3,/
120X.26FPTYPES FOR SUBDRAIN ,F5.2,6H \$/FT ,////2X)

C
C
C

C PART A

C PURPOSE

C THIS SECTION IS TO ESTABLISH A VALLE FOR SOIL SUPPORT,SSV.

C SSV =4.90*ALOG10(CAR)

C
C
C

C PART B

C PURPOSE

C THIS SECTION IS FOR THE SOLUTION OF THE EQUIVELANT 18K AXLE LOAD
C APPLICATIONS DURING THE LIFE TIME OF THE PAVEMENT.

16

ACTAD=(ACTI+ADT2C)/4.0
IF(NL.EQ.2) TLF=1.0
IF(NL.EQ.4) TLF=0.9
IF(NL.EQ.6) TLF=0.8
5 DO 200C I1=1,3
IF(I11.EQ.1) GO TO 6
IF(I11.EQ.2) PERMU=PERMU/2.0
IF(I11.EQ.3) PERMU=PERMU*3.0
IF(PERMU.GE.100.C) PERMU=100.C
6 IF=ADTAD*PERTRK*TLF*(PERMU*0.947+{10C.C-PERML}*0.117)/10000.0
W=TF*DP*365.0

C
C
C

C PART C

C PURPOSE

C THIS SECTION IS FOR THE SOLUTION OF THE STRUCTURAL NUMBER .

C COMPM=ALOG10(W)

SN=1.0

1001 SN=SN+1.0

EQW1=9.36*ALOG10(SN)-0.2C*ALOG10((CD-P)/(CD-1.5))/(10.40+1094./SN**

15.19)+0.37756*(SSV-3.0)-0.97*ALOG10(RF)

IF(EQW1.LE.COMPM) GO TC 1001

IF(EQW1.GE.COMPM) GO TC 1002

1002 SN=SN-C.1

EQW2=9.36*ALOG10(SN)-0.20*ALOG10((CO-P)/(CC-1.5))/(10.40+1094./SN**

15.19)+0.37756*(SSV-3.0)-0.97*ALOG10(RF)

IF(EQW2.GE.COMPM) GO TC 1002

50 51 52 53

37

39 40 41 42

MAIN - EFN SOURCE STATEMENT - IFN(S) -

DC040C0

```

1003 SN=SN+FCI
      IF(EQW2-LE-CCMPW) GO TC 1003
      EQW3=9.36*ALOG10(SN)-0.20+ALOG10((CO-P)/(CC-1.5))/10.40+1094./SN**
      15.19)+0.37756*(SSV-3.0)-0.97*ALOG1C(RF)
      IF(EQW3-LE-CCMPW) GO TC 1003
      IF(EQW3-GE-CCMPW) GO TO 1004
1004 P(2)=SN-1.0
C .....
C PART D
C PURPOSE
C .....
C THIS SECTION IS FOR DETERMINING THE ICIAL THICKNESS CF PAVEMENT.
      IF(DWL-LE-9CCO.) GO TO 8
      IF(CML-CE-1CCO.) GO TO 9
      8 P(3)=4.723461.037/CBR**1.05-45.180*EXP(-CBR)
      GO TO 10
      9 P(3)=4.423+52.736/CBR**0.90-19.884*EXP(-CBR)
      GO TO 10
      10 CONTINUE
C
      WRITE(6,20C) NL,PERML,P(2),P(3),TF
200 FORMAT(1I,15X,8H-SOLUTION,///
120X,34H-NUMBER OF LANES ..... ,3X,12,/
120X,34H-PERCENT MULTIPLE UNITS ..... ,F5.2,/
120X,34H-STRUCTURAL NUMBER ..... ,F5.2,/
120X,34H-TOTAL THICKNESS ..... ,F5.1,8H INCHES,/
120X,34H-TRUCK FACTOR ..... ,F6.0,8H 18K/DAY,// 2X)
C .....
C PART E
C PURPOSE
C .....
C THIS SECTION SELECTS THE OPTIMAL PAVEMENT ,BY THE MODIFIED LINEAR
PROGRAMING ALGORITHM.
      IF(NL-EQ-2) GO TO 1
      IF(NL-EQ-4) GO TO 2
      IF(NL-EQ-6) GO TO 3
C
C 2 LANES
C
      1 G(1)=(CK(1)*GEN(1)/24000.0)*24.0
      G(2)=(CK(2)*GEN(2)/24000.0)*24.0
      G(3)=(CK(3)*GEN(3)/24000.0)*24.0
      G(4)=(CK(4)/(12.0*27.C))*24.0
      G(5)=(CK(5)*GEN(5)/24000.0)*20.0*3.0
      G(6)=(CK(3)*GEN(3)/24000.0)*31.0*6.0
      G(7)=(C.075*CK(6)+CK(7))*1.1*2.0
      G(8)=(CK(4)/(12.0*27.0))*258.0
      G(9)=(CK(4)/(12.0*27.0))*(22.0+8(3)*C.666)

```

61 62 63 64

79 80

83 84

86

MAIN - EFN SOURCE STATEMENT - IFN(S) - OCC4CCD

G(10)=0.0
 G(11)=(CK(4)/(12.0*27.0))*50.0
 G(12)=(CK(4)/(12.0*27.0))*5.0
 G(13)=(CK(8)-CK(1))/(12.0*2000.0)*DEN(1)*(90.0/110.0)*24.0
 GO TO 12

C 4 LANES
 C

2 G(1)=(CK(1)*DEN(1)/24000.0)*24.0
 G(2)=(CK(2)*DEN(2)/24000.0)*24.0
 G(3)=(CK(3)*DEN(3)/24000.0)*24.0
 G(4)=(CK(4)/(12.0*27.0))*24.0
 G(5)=(CK(5)*DEN(5)/24000.0)*14.0*3.0
 G(6)=(CK(3)*DEN(3)/24000.0)*19.75*6.0
 G(7)=(0.075*CK(6)*CK(7))*1.1
 G(8)=(CK(4)/(12.0*27.0))*162.0
 G(9)=(CK(4)/(12.0*27.0))*14.375*8(3)*C.333
 G(10)=10.075*CK(6)*CK(7))*1.1
 G(11)=(CK(4)/(12.0*27.0))*60.0
 G(12)=(CK(4)/(12.0*27.0))*5.875
 G(13)=(CK(8)-CK(1))/(12.0*2000.0)*DEN(1)*(90.0/110.0)*24.0
 GO TO 12

C 6 LANES
 C

3 C(1)=(CK(1)*DEN(1)/24000.0)*36.0
 G(2)=(CK(2)*DEN(2)/24000.0)*36.0
 C(3)=(CK(3)*DEN(3)/24000.0)*36.0
 C(4)=(CK(4)/(12.0*27.0))*36.0
 G(5)=(CK(5)*DEN(5)/24000.0)*14.0*3.0
 G(6)=(CK(3)*DEN(3)/24000.0)*19.75*6.0
 G(7)=(0.075*CK(6)*CK(7))*1.1
 G(8)=(CK(4)/(12.0*27.0))*162.0
 G(9)=(CK(4)/(12.0*27.0))*14.375*8(3)*C.333
 G(10)=10.075*CK(6)*CK(7))*1.1
 G(11)=(CK(4)/(12.0*27.0))*60.0
 G(12)=(CK(4)/(12.0*27.0))*5.875
 C(13)=(CK(8)-CK(1))/(12.0*2000.0)*DEN(1)*(90.0/110.0)*24.0
 12 P(1)=3.0
 E(4)=-10.0
 P(5)=4.0
 IF(B(3).LE.20.0) GO TO 22
 IF(B(3).GE.20.1) GO TO 21
 21 YA(5,1)=10000.0
 GO TO 122

C 27 M=6
 A=2

P(6)=-10.0
 C(1)=G(1)
 C(2)=G(2)*1.041
 C(3)=0.0

C SUBPROBLEM 1, SECTION WITH NO SUBBASE
 C

C CASE 1
 C


```

C(4)=0.0
E=G(5)+G(6)+G(13)
CO 121 J=1,6
CO 121 K=1,2
121 A(J,K)=A1(J,K)
CALL MINITIA,NROW,8,C,C,M,N,O,S,PSOL,OSOL,KEAN)
YA(1,1)=PSOL(1)
YA(2,1)=PSOL(2)
YA(3,1)=0.0
YA(4,1)=0.0
YA(5,1)=S

```

122

```

C
C CASE 2
C

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```

122 P=5
N=2

```

```

C(1)=G(1)
C(2)=G(3)*1.041
C(3)=0.0
C(4)=0.0
E=G(5)+G(6)+G(13)
CO 221 J=1,5
CO 221 K=1,2
221 A(J,K)=A5(J,K)
CALL MINITIA,NROW,8,C,C,M,N,O,S,PSOL,OSOL,KEAN)
YA(1,2)=PSOL(1)
YA(2,2)=0.0
YA(3,2)=PSOL(2)
YA(4,2)=0.0
YA(5,2)=S

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136

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C
C CASE 3
C

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P=7
N=3
E(6)=-10.0
E(7)=4.0
C(1)=G(1)
C(2)=G(2)*1.041
C(3)=G(3)*1.083
C(4)=0.0
E=G(5)+G(6)+G(13)
CO 321 J=1,7
CO 321 K=1,3
321 A(J,K)=A2(J,K)
CALL MINITIA,NROW,8,C,C,M,N,O,S,PSOL,OSOL,KEAN)
YA(1,3)=PSOL(1)
YA(2,3)=PSOL(2)
YA(3,3)=PSOL(3)
YA(4,3)=0.0
YA(5,3)=S

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149

```

C
SSI(1)=AMINI(YA(5,1),YA(5,2),YA(5,3))
CO 123 I=1,3
IF(YA(5,1).LE.SSI(1)) IM=1
IF(YA(5,1).LE.SSI(1)) GO TO 1123

```



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MAIN          - EFN          SOURCE STATEMENT - IFN(S) -
              DC040CD

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```

123 CONTINUE
1123 C0 2123 KK=1,5
      YB(KK,1)=YA(KK,1M)

```

C
C
C SUPPLEMENT II, SECTION WITH SUBDRAIN
C
C
C CASE 4
C
C

```

P=8
R(6)=-10.0
R(7)=4.0
R(8)=-20.0
C(1)=G(1)+G(12)
C(2)=G(2)+1.041+G(12)
C(3)=G(4)+G(12)
C(4)=0.0
L=G(5)+G(6)+G(7)+G(10)-G(11)+G(13)
CO 421 J=1,8
CO 421 K=1,3

```

```

421 A(I,J,K)=A3(I,J,K)
CALL MINITIA,NROW,8,C,D,M,N,O,S,PSCL,DSOL,KEAN)
YA(1,4)=PSCL(1)
YA(2,4)=PSCL(2)
YA(3,4)=O.C
YA(4,4)=PSCL(3)
YA(5,4)=S

```

180

C
C
C

```

p=7
h=3
f(6)=4,0
f(7)=-20,0
C(1)=G(1)+G(12)
C(2)=G(3)+1.041+G(12)
C(3)=G(4)+G(12)
C(4)=0,0
C=G(5)+G(6)+G(7)+G(10)-G(11)+G(13)
CO 521 J=1,7
CO 521 K=1,3

```

```

521 A(J,K)=A6(J,K)
CALL MINITIA,NROH,B,C,D,M,N,O,S,P,SCAL,DSOL,KENN)
YA(1,5)=PSCAL(1)
YA(2,5)=0.0
YA(3,5)=PSCAL(2)
YA(4,5)=PSCAL(3)
YA(5,5)=S

```

193

C
C CASE 6
C

$$\begin{aligned} \mu &= 9 \\ \sigma &= 4 \\ p(6) &= -10.0 \\ p(7) &= 4.0 \end{aligned}$$

MAIN - EFN SOURCE STATEMENT - IFN(S) -

```

P(8)=4.0
B(9)=-20.0
C(1)=G(1)+G(12)
C(2)=G(2)+1.041+G(12)
C(3)=G(3)+1.083+G(12)
C(4)=G(4)+G(12)
C=G(5)+G(6)+G(7)+G(1C)-G(11)+G(13)
C0 621 J=1.9
C0 621 K=1.4
621 A(J,K)=A4(J,K)
CALL MINIT(A,NROW,8,C,C,M,N,0,S,PSCL,DSOL,KEAN)
YA(1,6)=PSOL(1)
YA(2,6)=PSOL(2)
YA(3,6)=PSOL(3)
YA(4,6)=PSOL(4)
YA(5,6)=S
C
SSI(2)=AMIN1(YA(5,4),YA(5,5),YA(5,6))
C0 456 I=4.6
IF(YA(5,1).LE.SSI(2)) IK=I
IF(YA(5,1).LE.SSI(2)) GO TO 1456
456 CONTINUE
1456 C0 2456 KK=1.5
YB(KK,2)=YA(KK,1K)
2456 CONTINUE
C
C SUBPROBLEM III, SECTION WITH SUBBASE THRU SHOULDER
C
C CASE 7
C
M=8
N=3
B(6)=-10.0
B(7)=4.0
B(8)=-20.0
C(1)=G(1)+G(9)
C(2)=G(2)+1.041+G(9)
C(3)=G(4)+G(9)
C(4)=0.0
C=G(5)+G(6)+G(10)-G(8)+G(13)
C0 721 J=1.8
C0 721 K=1.3
721 A(J,K)=A3(J,K)
CALL MINIT(A,NROW,8,C,C,M,N,0,S,PSCL,DSOL,KEAN)
YA(1,7)=PSOL(1)
YA(2,7)=PSOL(2)
YA(3,7)=0.0
YA(4,7)=PSOL(3)
YA(5,7)=S
C
C CASE 8
C
M=7
N=3
B(6)=4.0
B(7)=-20.0

```

206

237

MAIN - EFN SOURCE STATEMENT - IFN(S) -

C(1)=G(1)+G(9)
C(2)=G(3)*1.041+G(9)
C(3)=G(4)+G(9)
C(4)=0.0
C=G(5)+G(6)+G(10)-G(8)+G(13)
CO 821 J=1,7
CO 821 K=1,3

821 A(I,J,K)=A6(J,K)
CALL MINITIA,NROW,B,C,U,M,N,O,S,PSCL,DSOL,KEKN)
YA(1,8)=PSOL(1)
YA(2,8)=0.0
YA(3,8)=PSOL(2)
YA(4,8)=PSCL(3)
YA(5,8)=S

C
C CASE 9
C

M=9
N=4

B(6)=-10.0
B(7)=4.0
B(8)=4.0

B(9)=-20.0
C(1)=G(1)+G(9)
C(2)=G(2)*1.041+G(9)
C(3)=G(3)*1.083+G(9)

C(4)=G(4)+G(9)
C=G(5)+G(6)+G(10)-G(8)+G(13)
CO 921 J=1,9
CO 921 K=1,4

921 A(I,J,K)=A4(J,K)
CALL MINITIA,NROW,B,C,U,M,N,O,S,PSCL,DSOL,KEKN)
YA(1,9)=PSOL(1)
YA(2,9)=PSOL(2)
YA(3,9)=PSCL(3)
YA(4,9)=PSCL(4)
YA(5,9)=S

C

SSI(3)=AMIN1(YA(5,7),YA(5,8),YA(5,9))
CO 789 I=7,9
IF(YA(5,1).LE.SSI(3)) IN=1
IF(YA(5,1).LE.SSI(3)) GO TO 1789

789 CONTINUE

1789 CO 2789 KK=1,5

Y8(KK,3)=YA(KK,1N)

2789 CONTINUE

C

300 FORMAT(48X,9THICKNESS,/
120X,26HBITUMINOUS SURFACE ,F5.1,7H INCHES,/
120X,26HSTABILIZED BASE ,F5.1,7H INCHES,/
120X,26HCOMPACTED AGGREGATE BASE ,F5.1,7H INCHES,/
120X,26HGRANULAR SUBBASE ,F5.1,7H INCHES,///
136X,10PCOST .. ,F6.2,16H \$ PER LONG. FT.,//////)
SOPT=AMIN1(SSI(1),SSI(2),SSI(3))
CO 75 NI=1,3
IF(SSI(NI).LE.SOPT) GO TO 25

250

263

;

MAIN - EFN SOURCE STATEMENT - IFN(S) -

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75 CONTINUE
25 IF(NI.LE.1) GO TO 325
  IF(NI.LE.2) GO TO 625
  IF(NI.LE.3) GO TO 925
C
C
325 WRITE(6,4CC)
400 FORMAT(15X,16HOPTIMAL SOLUTION,///
120X,29HCROSS-SECTION WITHOUT SUBBASE,/)
  WRITE(6,3CC) (Y8(KK,1),KK=1,5)
  IF(SS1(12).LE.SS1(3)) GO TO 329
  GO TO 330
329 WRITE(6,8CC)
800 FORMAT(15X,3HALTERNATIVE SOLUTION (SL8OPTIMAL),///
120X,27HCROSS-SECTION WITH SUBDRAIN,/)
  WRITE(6,3CC) (Y8(KK,2),KK=1,5)
  WRITE(6,5CC)
500 FORMAT(15X,3HALTERNATIVE SOLUTION (SL8OPTIMAL),///
120X,43PCROSS-SECTION WITH SUBBASE THROUGH SHOULDER,/)
  WRITE(6,3CC) (Y8(KK,3),KK=1,5)
  GO TO 2000
330 WRITE(6,5CC)
  WRITE(6,3CC) (Y8(KK,3),KK=1,5)
  WRITE(6,8CC)
  WRITE(6,3CC) (Y8(KK,2),KK=1,5)
  GO TO 2000
C
C
625 WRITE(6,600)
600 FORMAT(15X,16HOPTIMAL SOLUTION,///
120X,27HCROSS-SECTION WITH SUBDRAIN,/)
  WRITE(6,3CC) (Y8(KK,2),KK=1,5)
  IF(SS1(11).LE.SS1(3)) GO TO 628
  GO TO 630
628 WRITE(6,70C)
700 FORMAT(15X,3HALTERNATIVE SOLUTION (SUBOPTIMAL),///
120X,29HCROSS-SECTION WITHOUT SURBASE,/)
  WRITE(6,3CC) (Y8(KK,1),KK=1,5)
  WRITE(6,5CC)
  WRITE(6,3CC) (Y8(KK,3),KK=1,5)
  GO TO 2000
630 WRITE(6,50C)
  WRITE(6,3CC) (Y8(KK,3),KK=1,5)
  WRITE(6,7CC)
  WRITE(6,300) (Y8(KK,1),KK=1,5)
  GO TO 2000
C
C
925 WRITE(6,900)
900 FORMAT(15X,16HOPTIMAL SOLUTION,///
120X,43HCROSS-SECTION WITH SUBBASE THROUGH SHOULDER,/)
  WRITE(6,30C) (Y8(KK,3),KK=1,5)
  IF(SS1(11).LE.SS1(2)) GO TO 929
  GO TO 930
929 WRITE(6,70C)
  WRITE(6,30C) (Y8(KK,1),KK=1,5)

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MAIN - EFN SOURCE STATEMENT - IFN(S) -

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WRITE(6,80C)
WRITE(6,30C) (YB(KK,2),KK=1,5)
GO TO 2000
930 WRITE(6,80C)
WRITE(6,30C) (YB(KK,2),KK=1,5)
WRITE(6,70C)
WRITE(6,30C) (YB(KK,1),KK=1,5)
C
2000 CONTINUE
STOP
ENC

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389
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396
401
402

```

$IBFTC MINX
SUBROUTINE MINIT(A,NROW,8,C,O,M,N,NE,S,PSOL,CSOL,KENN)
DIMENSION A(NROW,2C),B(15),C(15),PSOL(15),OSCL(15)
DIMENSION IND(101),IND1(51),ICLK(51),THMINIC(1),IPIN(101),
JMAX(51),DELMAX(51)
1
.....
SUBROUTINE MINIT
PURPOSE
MINIT SOLVES THE LINEAR PROGRAMMING PROBLEM BY THE MINIT
ALGORITHM (SEE METHOD FOR REFERENCES). THE PROBLEM IS
ASSUMED TO BE IN THE FOLLOWING FORM,

      A1 X + B1 .LE. 0
      A2 X + B2 .EQ. 0
           X .GE. 0
      MIN U=C + C*X

THE DUAL PROBLEM IS THEN,

      Y(1),...,Y(M-NE) .GE. C
      Y(M-NE+1),...,Y(M) FREE
      A' Y + C .GE. 0
      MAX V=C + B*Y

WHERE NE IS THE NUMBER OF EQUALITY CONSTRAINTS
A=(A1,A2,...) IS M BY N
A1 IS IM-NE) BY N
A2 IS NE BY N
B=(B1,B2,...) IS M BY 1
B1 IS (M-NE) BY 1
B2 IS NE BY 1
C IS M BY N
O IS A SCALAR

USAGE
CALL MINIT(A,NROW,8,C,O,M,N,O,S,PSOL,OSOL,KENN)
DESCRIPTION OF PARAMETERS
A - (M BY N) MATRIX OF COEFFICIENTS, DESTROYED

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MINX - EFN SOURCE STATEMENT - IFN(S) -

DURING COMPUTATION.
THE LAST NE ROWS OF A CORRESPOND TO THE EQUALITY.
CONSTRAINTS OF THE PROBLEM
B - M-VECTOR OF REQUIREMENTS.
C - N-VECTOR OF COSTS.
C - A CONSTANT ADDED TO THE OBJECTIVE FUNCTION.
M - NUMBER OF CONSTRAINTS-INEQUALITIES AND EQUALITIES.
(ROWS OF A).
N - NUMBER OF VARIABLES. (COLUMNS OF A).
NE - NUMBER OF EQUALITY CONSTRAINTS. THE LAST NE ROWS
OF A.
S - VALUE OF THE OBJECTIVE FUNCTION.
PSOL - (M+N)-VECTOR, PRIMAL SOLUTION. PSOL(N+1),...,
PSOL(M+N) ARE SLACK VARIABLES FOR THE PRIMAL
PROBLEM.
DSOL - (M+N)-VECTOR, DUAL SOLUTION. DSOL(M-NE+1),...,
DSOL(M+N) ARE SURPLUS VARIABLES FOR THE DUAL
PROBLEM.
KENN - DESCRIBES THE OUTCOME OF THE LP ALGORITHM
- KENN=-2 INDICATES THAT THE PRIMAL OBJECTIVE
FUNCTION IS UNBOUNDED, THE DUAL PROBLEM HAS NO
FEASIBLE SOLUTION.
- KENN=-1 INDICATES THAT THE DUAL OBJECTIVE
FUNCTION IS UNBOUNDED, THE PRIMAL PROBLEM HAS NO
FEASIBLE SOLUTION.
KENN=C INDICATES THAT AN OPTIMAL FEASIBLE SOLUTION
HAS BEEN FOUND AND STORED IN PSOL, DSOL, AND S.
- KENN=1 INDICATES THAT THERE IS NO SOLUTION.

REMARKS

THE CURRENT DIMENSION STATEMENT IS ADEQUATE FOR M .LE. 50,
AND N .LE. 50. IF THE USER WISHES TO CHANGE THE DIMENSION
STATEMENT TO SUIT HIS NEEDS, THE FOLLOWING FORM SHOULD BE
USED.
DIMENSION AIM(1,M+N-NE+1),B(M),C(N),PSOL(M+N),DSOL(M+N)
LOCAL ARRAYS,
DIMENSION IND(M+N-NE+1),INDI(M+1),ICHI(M+1),THMIN(M+N-NE+1),
IMIN(M+N-NE+1),JMAX(M+1),DELMAX(M+1)
THE USER SHOULD CHECK TO SEE THAT THE DIMENSION STATEMENT
OF MINIT AGREES WITH THE DIMENSION STATEMENT OF THE CALLING
PROGRAM.

METHOD

THE MINIT METHOD IS A MODIFICATION OF THE COMPOSITE SIMPLEX
METHOD. THE ALGORITHM WAS DEVELOPED BY ROBERT LLEWELLYN AND
IS PRESENTED IN,
LLEWELLYN,R.W.,LINEAR PROGRAMMING,HOLT, RINEHART AND
WINSTON, NEW YORK, 1964, PP. 207-227.
THE ALGORITHM WAS PROGRAMMED IN ALGOL BY RODOLFO C. SALAZAR
AND SUBRATA K. SEN, CARNEGIE INSTITUTE OF TECHNOLOGY,
GRADUATE SCHOOL OF INDUSTRIAL ADMINISTRATION, PITTSBURGH PA.

INITIALIZATION

DATE 08/06/69

DC040CD - IFN(S) -

MINX - EFN SOURCE STATEMENT

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IF (IR-GT,NE) GO TO 155
CMIN=1.0E+6
      GMIN IS SET EQUAL TO A LARGE NUMBER FOR INITIALIZATION PURPOSES

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C
C
C

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      L=1
      CO 110 J=1,N
      THMIN(J)=1.0E+6
      IF (A(1,J)) 109,110,11C
109  INO(L)=J
      L=L+1
110  CONTINUE
      IF (L-1) 120,120,130
120  CO 125 J=1,N
125  INO(J)=J
      L=L+1
130  CONTINUE
      LM1=L-1
      MNE2=M-NE+2
      CO 160 K=1,LM1
      JK=IND(K)
      CO 150 I=MNE2,M1
      IF (CHK(I)) 150,146,15C
146  IF (A(I,JK)) 150,150,147
147  THETA=A(I,LCOL)/A(I,JK)
148  THMIN(JK)=THETA
      IMIN(JK)=I
150  CONTINUE
      GAMMA=THMIN(JK)*A(I,JK)
      IF (GAMMA-CMIN) 155,16C,160
155  GMIN=GAMMA
      JMIN=JK
160  CONTINUE
      IM=IMIN(JMIN)
      IS=IM
      IT=JMIN
      ASSIGN 190 TO NTRANS
      GO TO 3000
190  CONTINUE
      IR=IR+1
      GO TO 100
195  CONTINUE

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C
C
C
C
C
C

END OF PHASE1

200 CONTINUE

MAIN ALGORITHM

L=1

K=1

CO 210 J=1,LCOL1

IF (A(1,J)*T0) 209,210,210

209 INO(L)=J

L=L+1

MINX - EFN SOURCE STATEMENT - IFN(S) -

OC040C0

C IND KEEPS TRACK OF THE COLUMNS IN WHICH A(I,J) IS NEGATIVE

210 CONTINUE

CO 220 I=2,M1

IF (A(I,LCOL)+TO) 215,220,220

219 IND(I,K)=1

K=K+1

220 CONTINUE

C

C IND1 KEEPS TRACK OF THE ROWS IN WHICH A(I,LCOL) IS NEGATIVE

C

IF(L-1) 229,225,229

225 IF(K-1) 226,400,226

226 IF (K-2) 300,227,300

227 CO 228 J=1,LCOL1

I1=IND1(I)

IF(A(I,J))300,228,228

228 CONTINUE

C

C PRIMAL PROBLEM HAS NO FEASIBLE SOLUTION, CLAL OBJECTIVE
FUNCTION IS UNBOUNDED

KENN=-1

RETURN

229 CONTINUE

IF (L-2) 240,230,240

230 IF (K-1) 500,231,500

231 CO 232 I=2,M1

J1=IND1(I)

IF (A(I,J1)) 232,232,400

232 CONTINUE

C

C PRIMAL OBJECTIVE FUNCTION IS UNBOUNDED, DUAL PROBLEM HAS NO
FEASIBLE SOLUTION

C

KENN=-2

RETURN

240 IF (K-1) 500,400,500

300 ASSIGN 302 TO NPH1

GO TO 2000

302 CONTINUE

IS=IMAX

IT=JM

ASSIGN 200 TO NTRANS

GO TO 3000

400 ASSIGN 401 TO NGAM

GO TO 1000

401 CONTINUE

IS=IM

IT=JMIN

ASSIGN 200 TO NTRANS

GO TO 3000

500 ASSIGN 501 TO NGAM

GO TO 1000

501 ASSIGN 502 TO NPH1


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MINX - EFN SOURCE STATEMENT -
GO TO 2000
502 CONTINUE
IF (GMIN-1.0E+6) 602,601,602
601 IS=IMAX
IT=JM
ASSIGN 200 TO NTRANS
GO TO 3000
602 IF (PHIMAX+1.0E+6) 604,603,604
603 IS=IM
IT=JMIN
ASSIGN 200 TO NTRANS
GO TO 3000
604 IF (ABS(PHIMAX)-ABS(GMIN)) 605,605,606
605 IS=IM
IT=JMIN
ASSIGN 200 TO NTRANS
GO TO 3000
606 IS=IMAX
IT=JM
ASSIGN 200 TO NTRANS
GO TO 3000
1000 CONTINUE
C
C BEGIN PROGRAMMA
C
C GMIN=1.0E+6
C
C GMIN IS SET EQUAL TO A LARGE NUMBER FOR INITIALIZATION PURPOSES
C
JMIN=0
LONE=L-1
CO 102C L1=L,LONE
INDL1=IND(L1)
IMIN(INDL1)=0
THMIN(INDL1)=1.0E+6
CO 101C I=2,M1
IF (.NOT.((A(I,INDL1).GT.TO).AND.(A(I,LCCL).GE.--TO))) GO TO 1010
THETA=A(I,LCOL)/A(I,INDL1)
IF (.NOT.(THETA-1. THMIN(INDL1))) GO TO 101C
THMIN(INDL1)=THETA
IMIN(INDL1)=1
1010 CONTINUE
GAMMA=1.0E+8
IF (THMIN(INDL1) .NE. 1.0E+6) GAMMA=THMIN(INDL1)*A(I,INDL1)
IF (GAMMA .GE. GMIN) GO TO 1020
GMIN=GAMMA
JMIN=INDL1
1020 CONTINUE
IF (JMIN .GT. 0) IP=JMIN(JMIN)
GO TO NGAM,(401,501)
C
C END OF PROGRAMMA
C
2000 CONTINUE
C
C BEGIN PROPHI
C

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MINX	-	EFN	SOURCE STATEMENT	-	IFN(S)	-
			DC040CD			

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C      PHIMAX=-1.OE+6
C
C      PHIMAX IS SET EQUAL TO A SMALL NUMBER FOR INITIALIZATION
C      PURPOSES
C
C      IMAX=0
C      KONE=K-1
C      CO 2020 KI=1,KONE
C      INDIKI=INDI(KI)
C      JMAX(INDIKI)=0
C      CELMAX(INCIKI)=-1.OE+6
C      CO 201C J=1,LCCOL I
C      IF (.NOT.(A(INDIKI,J).LT.-TD).AND.(A(I,J).GE.-TD))) GO TO 201D
C      CELTA=A(I,J)/AT(INDIKI,J)
C      IF (.NOT.(CELTA.GT.DELMAX(INDIKI))) GO TO 201C
C      CELMAX(INCIKI)=DELTA
C      JMAX(INDIKI)=J
C
C      201D CONTINUE
C      PHI=-1.OE+8
C      IF (DELMAX(INDIKI) .NE. -1.OE+6) PHI=DELMAX(INDIKI)*A(INDIKI,LCCOL I)
C      IF (PHI .LE. PHIMAX) GO TO 2020
C      PHIMAX=PHI
C      IMAX=INDIKI
C
C      2020 CONTINUE
C      IF (IMAX .GT. 0) JM=JMAX(IMAX)
C      GO TO NPHI,(302,502)
C
C      END OF PROPHI
C
C      3000 CONTINUE
C
C      BEGIN ROWTRANS(IS,IT)
C      PERFORM THE USUAL PIVOT OPERATION WITH A(IS,IT) AS PIVOT
C      ELEMENT
C
C      IF ((IS .NE. 0).AND.(IT .NE. 0)) GC TO 3010
C      KENN=1
C
C      NO SOLUTION
C
C      RETURN
C      3010 CONTINUE
C      CUMMY=A(IS,IT)
C      CO 3030 J=1,LCCOL
C      A(IS,J)=A(IS,J)/CUMMY
C      CO 3050 I=1,M1
C      IF (I.EQ.IS) GO TO 305C
C      IF (A(I,IT).EQ.0.0) GO TO 305D
C      CUMMY=A(I,IT)
C      CO 3040 J=1,LCCOL
C      A(I,J)=A(I,J)-A(IS,J)*CUMMY
C      3050 CONTINUE
C      ICCH(IS)=IT
C      GO TO NTRANS,(200,190)

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MINX

- EFN

END OF ROWTRANS

C

4000 CONTINUE

C

BEGIN RESULTS

C

S=-A(I,LCOL)

MN=M+N

DO 4010 I=1,MN

PSOL(I)=0.0

CSOL(I)=0.0

4010

C

FIND PRIMAL SOLUTION VECTOR

C

DO 4020 I=2,M1

ICHKI=ICHKI(I)

4020 PSOL(ICHKI)=A(I,LCOL)

DO 4030 J=N1,LCOL1

JN=J-N

4030 CSOL(JN)=A(I,J)

DO 4040 J=1,N

JN=J+LCOL1-N

4040 CSOL(JN)=A(I,J)

KEAN=0

RETURN

END

\$DATA

EXECUTION

APPENDIX B
INPUT DATA INSTRUCTIONS

The input data is summarized on two computer cards. The value of the parameters are to be assigned by the designing engineer using the algorithm; they include soil and traffic characteristics, planning period, environmental factors and materials cost and densities.

Card 1

The first Card has twelve parameters.

Parameter	Format	Symbol	Description
1	I2	NL	Number of lanes; 2,4, or 6
2	F7.2	CBR	CBR value of the subgrade
3	F7.0	ADT ₁	Initial daily traffic in both directions
4	F7.0	ADT ₂	Terminal daily traffic in both directions
5	F7.2	DP	Design period of pavement
6	F7.2	TR	Percentage of trucks in traffic stream
7	F7.2	CT	Percentage of combination trucks in truck streams
8	F7.0	DEL	Design Wheel load 8 Kips or 10 Kips
9	F7.2	RF	Regional Factor
10	F7.2	P	Pavement terminal serviceability
11	I5		Estimated Construction year
12	I5		Estimated pavement retirement year

Card 2

The second card has twelve parameters.

Parameter	Format	Symbol	Description
1	F7.2	C ₁	Unit cost of bituminous surface, \$/Ton
2	F7.2	C ₂	Unit cost of stabilized base, \$/Ton
3	F7.2	C ₃	Unit cost of compacted aggregate base, \$/Ton
4	F7.2	C ₄	Unit cost of granular subbase, \$/YD ³
5	F7.2	C ₅	Unit cost of shoulder surface, \$/ton
6	F7.2	C ₆	Unit cost of subrain fill, \$/YD ³
7	F7.2	C ₇	Unit cost of subrain pipe, \$/Ft
8	F7.2	C ₈	Unit cost of wearing surface course, \$/Ton
9	F7.2	D ₁	Density of bituminous surface, lb/ft ³
10	F7.2	D ₂	Density of stabilized base, lb/ft ³
11	F7.2	D ₃	Density of compacted aggregate base, lb/ft ³
12	F7.2	D ₄	Density of shoulder surface, lb/ft ³

